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RESEARCH PAPER

Consuming Fuel and Fuelling Consumption: Modelling Human Caloric Demands and Fuelwood Use

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Abstract This paper describes a conceptual framework that was developed to integrate livestock, human, cultivation and forest constraints to model community fuelwood consumption over a 25-year planning horizon. This framework was constructed as an energy balance based on human caloric requirements in order to examine the effects of household-level decisions for nutrition, fuelwood and land use. A scenario from a virtual community in Uganda is presented to illustrate the utility of this model to allow rapid policy and scenario evaluation. User-defined inputs combined with published research data are used in simulating resource responses and energy consumption rates. This model is a potential tool to monitor fuelwood consumption and to understand the implications of various land-use practices.

Keywords Community resource use plan · Integrated planning · Human caloric requirement

Introduction

Rural communities in developing countries depend extensively on natural resources to sustain their livelihoods (Rennie and Singh 1996). Households undertake a wide range of activities and individuals make conscious choices through deliberate land-use strategies in order to best deploy assets and maintain their livelihoods. For

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communities and individuals so closely bound to the environment, natural resources must be carefully managed and monitored to meet current demands and to ensure supplies in the future (Warner 2000).

Forests continue to be central to livelihood systems. There is no clear estimate of the number of people dependent on forests to sustain their livelihoods, but Byron and Arnold (1999) placed it between 250 million and 1 billion people worldwide. In developing countries where nearly 90% of woodfuel worldwide is produced and consumed (Dovie et al. 2004; Naughton-Treves et al. 2007), almost every facet of human life is indirectly or directly connected with forest production. Forest resources in small rural communities are used to meet daily needs in many ways, for example supplemental nutrition, crafts, indigenous medicines, building materials and fuelwood. The vast majority of people in these communities are subsistence-based farmers in small rural communities. Fuelwood plays an especially vital role for them, providing energy to cook and process food. Therefore, fuelwood consumption must be better understood in order to explore the potential options to address resource shortages and forest decline (MacDonald et al. 2001; Pattanayak et al. 2004).

Existing literature does not adequately describe the types of relationships that exist between tropical forests and the people who currently use them (Byron and Arnold 1999). The models that have been developed to describe these relationships have remained descriptive, narrowly focused and site specific, making extrapolation from case study findings difficult (Byron and Arnold 1999). Analysing livelihoods is an integrative process, assessing micro and macro-level effects of land-use decisions through new technology (Hoon et al. 1997).

Livelihoods depend on their spatial linkage with natural resources (Salafsky and Wollenberg 2000). Many attempts to integrate complex sets of knowledge and the interests of diverse sets of actors into a common framework have yielded disappointing results. While interest in integration may exist, success on the ground has been limited (Sayer and Campbell 2004). New approaches are necessary—ones that are more inclusive of other measurable parameters, and that are integrative, multi-scalar and multi-temporal.

Modelling is one approach that helps researchers explore options and their implications (Haggith and Prabhu 2003; Standa-Gunda et al. 2003). The task of generating quantifiable outcomes for household decisions and land impacts is difficult, largely because of the data collection time and cost involved. Models simplify complex multi-dimensional processes and highlight a selected set of variables and causal relations involved in land-use change (Kaimowitz and Angelsen 1998; Geist and Lambin 2001). Variables and constraints can be useful in understanding patterns and processes of resource consumption and land use. However, little work has been done to integrate household inputs, resource constraints and labour allocation attributable to forest product activities at multiple scales (Tole 1998; Warner 2000).

Many approaches to modelling have focused on the impacts of land uses at more coarse scales. Stéphenne and Lambin (2001) developed a simulation model to project land-cover changes at a national scale, compiling exogenous variables (including population growth, livestock numbers and cereal imports) to predict

annual land allocation to fuelwood and crops and pasture. Shreier et al. (1991) derived a GIS-based model to determine regional food surpluses and deficits based on fuelwood usage in Nepal. In addition to these landscape-level approaches to resource consumption, other models have focused on smaller scales. Human interaction with the environment forms a critical component in shaping the landscape. These interactions with the natural resource base should be modelled to better understand the processes at work (Vanclay 2003). Scherr (2000) and Legg and Brown (2003) have worked to create conceptual frameworks describing resource extraction within agricultural communities. Chedid et al. (1999) applied a fuzzy programming approach to energy resource allocation. FAO (1983, 1987, 1993), Reddy et al. (1997), Siteur (1997) and Mabugu et al. (1998) have researched wood energy consumption and methods to improve consumption efficiency. Other models have approached fuelwood consumption through resource and labour valuation (MacDonald et al. 2001, Pattanayak et al. 2004) and through fuelwood harvesting schedule models (Bacaër et al. 2005).

This paper describes a new framework that emphasizes the interaction among components and processes in a landscape by tracking the cumulative effects of individual and household fuelwood consumption at the community level as a function of daily caloric requirements. It also illustrates the possibility of malnutrition based on upper-end caloric demands. This model was constructed to show the effects of small decisions on an annual and a quarter century scale. The model structure is flexible and general enough to be applied across regions and to allow rapid evaluation of scenarios. In the following sections, model development and construction are discussed. One scenario representing uncontrolled and unsustainable fuelwood consumption from a 'virtual village' in Uganda is then analyzed. Concluding comments follow.

Background to Model Development

Livelihoods are the combination of and access to assets and activities that together determine the well-being of an individual or household (Ellis 2000). Livelihoods in rural communities are complex and their make-up is not only affected by household activities, but also by spatial allocation of resources (Ellis 1998; Bryceson 2002). Livelihoods depend on the interaction of five types of assets drawn upon by individuals to build their respective livelihoods: natural, social, physical, financial and human capital (Carney 1998). This set of assets is interconnected with a household's vulnerability context, consisting of shocks, seasonality trends, sickness and other expected or unexpected changes. As the vulnerability context changes, so does the household's set of assets and as assets for individuals and households change over time, the vulnerability to shocks can improve or worsen. Each of these assets is susceptible to perturbations, and individuals develop coping strategies to respond to and mitigate harmful impacts. This becomes an iterative process as individuals and households work to sustain their livelihoods by securing interdependent assets. Therefore, the total livelihood of rural households needs to be understood as a system of decision-making, production, and consumption of

environmental resources (Dovie et al. 2004). The framework described in this paper adds to that understanding by reflecting in its construction some of the key internal dynamics of a livelihood system.

The framework targets two key assets—natural (fuelwood) and human (human ability to do work)—to meet caloric needs. Both natural and human assets cannot operate in isolation from the choices available to individuals and the outcomes of land-use strategies. Furthermore, as forest dependence continues to increase within growing communities, forest land conversion is probable. The 'immerization theory' attributes most deforestation to expanding subsistence smallholders and shifting cultivator populations who have limited economic opportunities and therefore must clear additional land for cultivation or fuelwood production (Geist and Lambin 2001). Within the sustainable livelihoods approach, this theory provides the basis to construct a new fuelwood consumption framework.

Fundamental to this framework are concepts introduced in three models. First, MacDonald et al. (2001) constructed a behavioural model of choice for fuelwood collection in north-eastern Zimbabwe. They asserted that choosing to collect and use fuelwood is one of a series of choices that households make in allocating labour and resources. These choices and activities in turn shape the landscape. This model is one of the first to describe changes in forest resources in terms of individual caloric expenditures, based on a series of interconnected constraints at the individual and farm level, but operating within the prevailing economic valuation paradigm.

Second, Shreier et al. (1991) described a spreadsheet model that determines how much consumable food, livestock feed and fuelwood would be produced in 75 districts in Nepal, based on agricultural, physiological and silvicultural constraints. This model uses regional and national level data sources when calculating food surplus and deficit amounts for individuals. These values are in turn scaled up to the regional level to determine resource sustainability and broader human impacts as various scenarios are evaluated at the regional level. This type of model can be useful to resource managers, but needs to be designed at a finer spatial scale to be applied to individual communities.

Third, the Forest Land Oriented Resource Envisioning System (FLORES) examines dynamics of interactions between the biophysical and socio-economic components of rural communities living at the forest margin and largely dependent on the land around them (Vanclay 2003, 1995). This approach focuses on landscape-scale changes as a result of household and field-level land-use activities. Within the FLORES model, sub-models describe functional interactions of actors, resources, cultivation and other activities to secure household livelihoods. The FLORES model is a framework or mechanism for testing and refining ideas conceived for a small village and scaled up to broader landscapes (Vanclay 1998). FLORES provides an adaptive, integrative modelling framework, but does not use caloric expenditures as the basis for its analysis.

The framework presented in this paper integrates concepts contained within these three models to construct a model for fuelwood consumption in a subsistence-based rural community as a function of fulfilling individual and household-level energy requirements. Human caloric requirement determines food need (as shown in

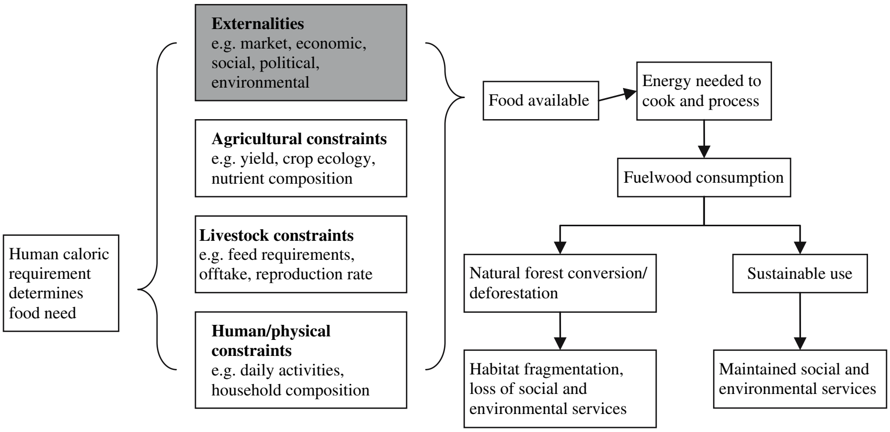

Fig. 1 Relationship of human caloric requirements and fuelwood consumption

Fig. 1). However, the amount of food produced, constrained by externalities and agricultural, livestock and human constraints, may be different from the amount of food available. It is assumed that all of the components in the model are deterministic (though probability distributions could be used to create stochastic components).

Energy is needed to process and cook available food, leading to fuelwood consumption. At this point, there are two possible paths. One type of fuelwood consumption is sustainable, where wood resources are used responsibly and monitored. Fuelwood is harvested with minimum impact, trees are replanted, little soil is lost, soil fertility is maintained, and land-use practices do not threaten future forest productivity. There is a system of environmental checks and balances. However, unsustainable harvest levels can have negative impacts such as habitat fragmentation and loss of environmental services. This type of fuelwood consumption may lead to forest conversion or to encroachment of unprotected natural forests and, some scientists argue, to deforestation (Wallace 1995; Black and Sessay 1997; Kayanja and Byarugaba 2001; FAO 2003). As more land is converted, the landscape becomes increasingly fragmented, and communities lose important social and environmental services offered by forests.

This model focuses on cultivation, livestock and human constraints (Fig. 1) that determine the food need and availability, which in turn drives fuelwood consumption.[1] Model development of this kind, however, is dependent upon data availability, quality and comparability as well as some fundamental assumptions. Table 1 lists key assumptions. The parameters of the model have been derived on the basis of a comprehensive literature review (mostly of community-scale case studies) reported in scientific journals, NGO publications and government reports. The model is limited to smallholder farmers in Sub-Saharan Africa, but the structure

[1] While externalities are important, their makeup can be unique for each locale and household. This framework omits these externalities and focuses only on agricultural, livestock and human and physical constraints.

Table 1 Assumptions of the model

Fuelwood consumption	(a) The average meal size for each meal for an average family is constant
	(b) Cooking efficiency for fuelwood is constant for each day
	(c) Houses remain heated during the colder months
	(d) There is a uniform use of fuelwood for the entire community for each year
	(e) Proportional fuelwood use can change only on an annual basis
	(f) One mature woman gathers all fuelwood for each household
Agricultural product consumption	(a) Specific fuelwood consumption (kg of product) is given only for cassava and maize. Values for millet, potatoes, sweet potatoes, beans and bananas are based on these values
	(b) Daily consumption is the same for both men and women for the entire community and is uniform throughout the year
	(c) Agricultural land is located at the village centre and radiates outward
Livestock product consumption	(a) Feed requirements to produce milk and beef are the same per unit of output
	(b) The area of land needed to raise feed for the chickens is negligible
	(c) Cattle begin grazing at the outer edge of the crops
Human caloric requirement	(a) Women's daily tasks do not change except for amount of time spent on fuelwood collection
	(b) The calories per kilometre burned during fuelwood collection are the same each year
	(c) Men's daily tasks do not change
	(d) There is no distinction between types of calories and the daily requirement for different food groups (i.e. proteins, carbohydrates, sugars)

is sufficiently flexible to allow inputs from other regions. It assumes a strong reliance on a neighbouring forest resource base, and hence may be less applicable to arid regions and those lacking forests.

Construction of the Model

A deterministic model has been developed that computes the caloric requirements to produce the energy required to meet the maintenance and growth needs for an individual in Sub-Saharan Africa. The needs of individuals are summed to show the broader-scale impacts. The model is an energy-based model because it computes the nutritional calories required per individual, and also the energy required for preparing food as well as home heating, for the villagers. With a growing population and caloric demand, fuelwood caches immediately adjacent to the community will be exhausted and the distance travelled to collect fuelwood will increase. Assuming more consumption than the amount reforested, fuelwood gathering could further degrade the landscape. Using a series of spreadsheets, data synthesis in this model consists of a series of steps, as shown in Box 1 and Fig. 2. User-defined inputs including household size, fuelwood species, population increase, and community size constitute initial (year 0) conditions. Based on a mass and energy balance, human caloric intake must be adequate to perform daily tasks. Estimates of the

Box 1 Parameters of the energy balance model

Number in household	Initial land fallow (ha)
Number of families in community	Initial distance to fuelwood (km)
Mean mass of man (kg)	Dist. to nearest forest (km)
Mean mass of woman (kg)	Initial daily caloric intake (kcal)
Total land held/household (ha)	Annual population increase (%)
Initial land allocated to cult. (ha)	Available fuelwood species
Initial land allocated to pasture (ha)	

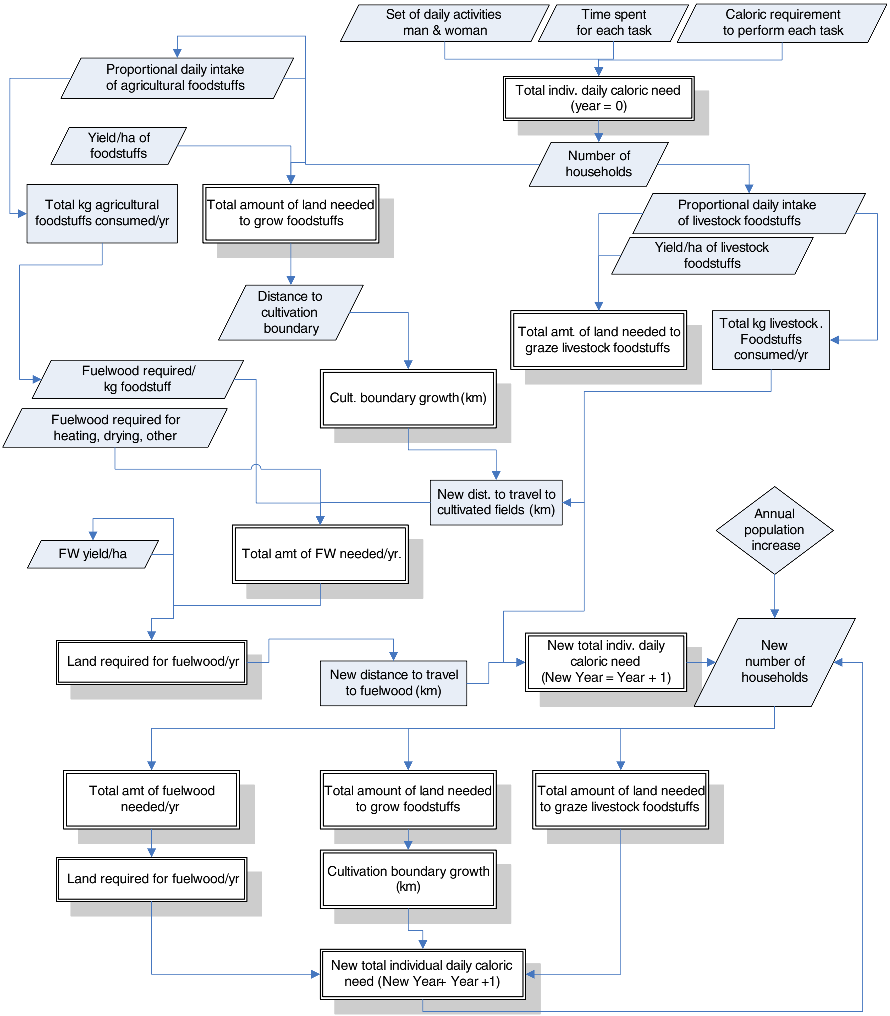

Fig. 2 Flowchart of the calorific intake model

required inputs are used to calculate annual individual human caloric needs and annual fuelwood consumption.

The first step of model construction addresses the physical capabilities of humans and their daily caloric intake, daily time budget of activities, and distances required to reach fuelwood. Using energy, land and other requirements, the model is designed to estimate family and community level caloric and fuelwood needs for a period of 25 years.

The average adult male and female body weight and resting metabolic rate are estimated. Daily tasks of females consist of food processing, cooking, and child rearing, farming and gathering water. Women and children collect firewood and no outside labour is used, as Gesist and Lambin (2001 suggest). There is a uniform caloric requirement and fuelwood consumption across all individuals regardless of age and gender. Daily tasks for males include hunting, livestock tending, coffee production, brewing and farming. The time spent doing each activity is estimated, and the amount of calories burned per unit of time during each task was obtained from McArdle et al. (1996). Caloric requirements are considered for adolescents and both male and female adults. Depending on activity level, caloric demand for males can be 2,500–3,500 kcal/day, and for women from 2,300 to 2,600 kcal/day between the ages of 30 and 59 years old (FAO 2001). Weight is highly correlated to total energy expenditure in children and adolescents. For adolescents aged 13 or 14 years and averaging 48 kg, the daily caloric requirement is between 2,500 and 2,700 for females, being greatest for males (FAO 2001). Children as young as 13 typically participate fully in household chores, work in the fields and collect water and firewood. Younger children are not considered in the model because, although they may participate in some tasks, they are weaker than adults and spend more hours of their day in school and are therefore not available to complete daily tasks. Also, younger children typically have a lower body mass and therefore require fewer calories. By appropriately assuming a uniform caloric need among family members, this model can explore the possibility of malnutrition and fuelwood consumption. These energy needs are extrapolated to annual values per adult equivalent.

Once the total number of calories required daily is calculated, this value goes to the livestock and cultivation tables to determine the amount of food in each category that must be consumed. The appropriate food proportions are determined using the FAO's Food Balance Sheet (FAO 2000). The fuelwood used to cook and process this food can then be calculated, following the steps outlined in Fig. 3.

From the amount of fuelwood required to fulfil caloric requirements, a new mean distance to fuelwood supplies is calculated. As individual and aggregate community caloric needs increase, households must cultivate more land and have more livestock to fulfil these demands. Thus, the total land used by the community increases. As food demands per household, the amount of fuelwood required to process and cook this food will increase. Fuelwood demand will also increase due to population growth. Therefore, the minimum distance to fuelwood resources increases. Women must now travel longer distances, make more trips to collect fuelwood and cultivate more land, daily caloric requirements will increase. This 'new' caloric requirement for women becomes the input for the model calculations

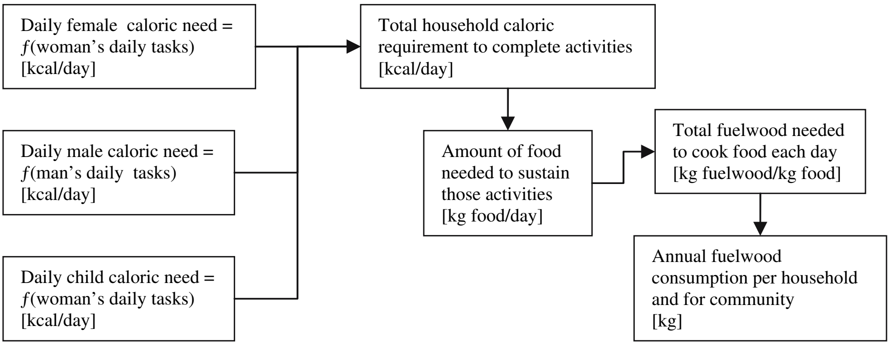

Fig. 3 Flowchart for annual fuelwood consumption sub-process

for the next year. As new caloric needs for individuals are calculated, the model continues to generate output for successive years within this positive feedback process.

The new outer fuelwood radius is used to determine the new annual caloric requirement. Since the distance travelled to collect fuelwood has increased, the new total amount of calories burnt for fuelwood collection can be obtained. The calories needed for fuelwood collection for women and children are then added to the calories needed to perform other daily tasks. This new caloric requirement is combined with the male caloric requirement to derive a new household and individual daily caloric requirement.

Scenario to Demonstrate Use of the Model

A scenario has been developed to demonstrate the potential of such a modelling effort. A scenario is a story of what might be (Wollenberg et al. 2000) and is useful to adjust parameters and scrutinize the output (Standa-Gunda et al. 2003). Natural resource systems are inherently complex and scenarios can be useful tools to assess possible changes in the system (Vanclay 2003; Standa-Gunda et al. 2003).

The case study setting is Sub-Saharan Africa, where there has been a high rate of natural forest loss. In Uganda alone, less than 3% of the land is covered by closed forest and it is estimated that approximately 2% of this land (110 km^2) is lost annually (Struhsaker 1987). The primary reasons for deforestation are attempts to meet fuelwood demands and the expansion of subsistence farming to meet the food demands of a growing population. Nearly 99% of Uganda's population is dependent on fuelwood to meet their cooking and heating needs (NEMA 2001).

Details for this scenario are derived from published data, showing the continual expansion of fuelwood reserves into the adjacent unprotected natural forest. In this scenario, the sole fuelwood source for the community is the natural forest. Because fuelwood is consumed, stands do not naturally regenerate and with the growing fuelwood demand community members have to travel greater distances to collect fuelwood in successive years. It is assumed that the community remains settled in

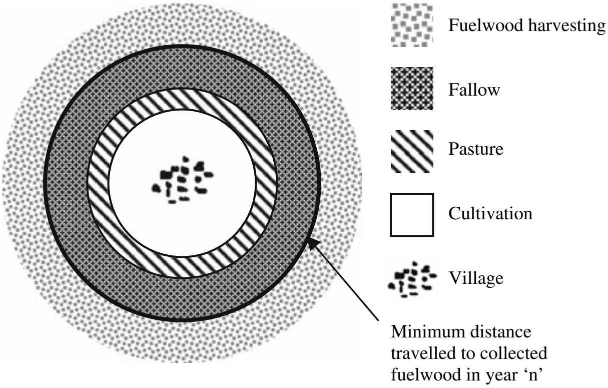

Fig. 4 Virtual community in year 'n'

the initial location throughout the 25-year forecast period, and crops yields are constant. It is further assumed that cultivation would be located as close as possible to the community boundary and fuelwood sources are beyond the zone of cultivation (Fig. 4). In Uganda where fuelwood dependence is high and natural regeneration is slow (Kayanja and Byarugaba 2001), this case represents a worst-case scenario for this region. The virtual community is shown in Fig. 4. The community uses wood cut from the natural forest to meet fuelwood needs and does not reforest harvested areas. As more fuelwood is needed, the minimum distance travelled to collect fuelwood increases in successive years. Other input values are indicated in Table 2.

Results and Discussion

In the scenario developed above, year 1 reflects the initial condition of 50 families in the community and in this year there is predicted to be an aggregate energy consumption of 3,595 kcal daily, requiring 4,382 kg of fuelwood to supply the family's cooking and heating needs. The simulation run tracks annual household fuelwood consumption. The simulation outputs for years 1, 8, and 25 for this scenario are summarized in Table 3.

Table 2 Scenario inputs for the initial model

Parameter	Value	Parameter	Value
No. persons in household	5	Total land held per household (ha)	1.5
No. of children in household at working age	3	Initial land dedicated to agriculture (ha)	0.5
No. of households	50	Initial land dedicated to pasture (ha)	0.5
Mean weight of men (kg)	77	Initial land fallow (ha)	0.5
Mean weight of women (kg)	59	Initial distance to fuelwood (km)	0.5
Annual population increase	3.0%	Distance to nearest natural forest (km)	2

Table 3 Land use allocations and locations for years 1, 8, 25

Year	No. of households	Avg. indiv. daily caloric need (kcal)	Household fuelwood need (kg/year)	Land needed for cultivation (ha)	Land needed for livestock (ha)	Land need for fuelwood (ha)	Cultivation boundary (m)	Pasture boundary (m)	Distance to fuelwood from village ctr. (m)
1	50	3,595	4,382	28.9	2.20	13.4	291	84	541
8	61	3,762	5,792	42.0	4.25	21.8	346	116	857
25	102	3,843	5,892	79.9	7.18	36.7	481	151	1,519

Using estimates of the energy consumption rates for each task, the average caloric need for a household member was 3,309 kcal in year 1, 3,595 kcal in year 8 and 3,843 kcal in year 25. As the fuelwood collection radius grows, women and children have to expend more energy, and the dietary caloric need increases, so the aggregate household fuelwood consumption should increase. However, the change in fuelwood consumption may be smaller than expected because daily caloric need is based on average household consumption.

As the average daily caloric need increases, each family will consume more fuelwood. Table 4 reports fuelwood consumption calculations from the model for both the family and community. Fuelwood consumption for heating remains constant while household consumption for cooking increase as a result of increased food demand. In aggregate, the community would require 13.4 ha of land specifically for fuelwood and 28.9 ha to meet the subsistence-based agriculture and livestock needs.

Tables 3 and 4 summarize the predicted aggregate annual community consumption of fuelwood and the distance required to travel to the nearest source of fuelwood. As harvesting continues in the natural forest and trees are not replanted, the fuelwood boundary continues to grow outward. At year 25, the radius has grown nearly 1 km, encompassing 36.7 ha to support the fuelwood needs.

These results demonstrate the linkage between fulfilling nutritional needs, fuelwood consumption and land-use requirements. As nutritional demands increase, the need for cultivation land and fuelwood increases. Therefore, the distance travelled to reach resources, particularly fuelwood, continues to increase outward from the village. From the simulation, the minimum fuelwood collection distance is 1.52 km after 25 years. Thus, there is immense pressure from the growing population on the residual natural forests. Under these conditions and as community members seek to meet short-term sustainability needs, encroachment into natural forestland continues.

On a basic level, the current model can be considered an adequate representation of fuelwood radius growth. Hamilton (1984) reported an average fuelwood distance in 1966 of 0.48 km in western Uganda and 15 years later, the fuelwood radius had increased to 1.57 km, which is in agreement with the model results of this study; initially, the fuelwood radius was set at 0.5 km and increased to 1.52 km fuelwood radius in the simulation for 25 years.

Table 4 Fuelwood consumption estimates for simulation years 1, 8, and 25

Year	Distance to fuelwood (m)	Household fuelwood use (kg/week)	Household fuelwood use cooking (kg/year)	Household fuelwood use heating (kg/year)	Community fuelwood use (kg/year)
1	500	62.5	3,250	1,132	219,097
8	762	63.9	3,325	1,132	274,074
25	1,323	64.8	3,372	1,132	457,749

Limitations of the Model and Possible Future Extensions

Although the model has been developed to an operational level, some shortcomings are recognized. The model is limited to smallholder agriculturalists in Sub-Saharan Africa, but was constructed in a sufficiently general form to allow inputs from other regions (e.g. south-east Asia and South America). It is based on a strong reliance on a neighbouring forest resource base, and may be less applicable to arid regions with sparse forest cover. Reliability of outputs is reduced if default parameters have to be used. The social and political interactions (e.g. marriage, land tenure), while recognized as important components to rural livelihoods within communities, have not been modelled.

The analysis for the Ugandan scenario illustrates that a community can meet fuelwood needs only if it can push its land use outward without penalty, that is, without physical, social or political constraints. However, this assumption is not realistic. Other neighbouring communities and urban areas also consume forest resources. Growth in community population and land use must be bounded by constraints including food availability, local geography and landholding boundaries. Local geography—including rivers, forest, grassland and hills—determines where the community can grow.

While the model is limited by a small number of parameters, it is necessary to first make a model simple and accessible model in order to examine critically each component (Vanclay 2003). The limitations of this framework also serve to pinpoint where further model development is needed. At present, there has been no formal validation of this model other than through scenario development. A more detailed case study is necessary to identify further model development constraints and measure energy inputs and outputs at the household and community levels. Incorporating a spatially explicit dataset using a geographic information system (GIS), the model could determine the spatial distribution of fuelwood extraction over a given planning horizon. Further integration of GIS mapping tools could show the pattern of expansion and contraction of cultivated land, pasture and fuelwood reserves over time as a function of resource availability. Fuelwood consumption is also dependent on species selection because different species have different heat capacities (kJ/kg), biomass yield (kg/ha/year), and mean annual growth increment. In situ data collection can be used to identify species selection and consumption patterns and to provide information for specific community model construction.

Conclusion

There has been little research on how to integrate community and resource utilization constraints at multiple spatial and temporal scales. The model introduced in this paper was constructed to show the interconnected nature of fuelwood consumption to household and land-use practices on an annual and a quarter century. The model provides a general quantitative overview of the effects of human nutritional (caloric) demand and its impact on land use and resource consumption. It is a useful tool in the evaluation of land management strategies. From these results,

it is evident that in order to meet fuelwood needs, a community must devise a resource management plan that includes an integration of cultivation, fuelwood and livestock. Of more importance, though, is the fact that people work to secure livelihoods and any management plan must consider human nutritional demands and population growth. With this model, the process of determining land-use strategies can be better organized. While this model may be limited in its applicability and complexity, it serves to illustrate a framework for understanding the role of human caloric intake and its impact on forest degradation.

The goal of developing such a model is to produce an evaluation tool applicable to various land management strategies as a means to organize better the assessment and monitoring process. Although this model is limited by the number of parameters considered, it serves as an indicator of the additional work that could be done to represent community fuelwood consumption. This model can be used to understand the implications of various land-use practices.

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